Recent On-Orbit Results and ARQ Performance Analysis for the TBIRD 200-Gbps Mission

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***Abstract*—The TeraByte Infrared Delivery (TBIRD) mission has successfully demonstrated 200-Gbps laser communication downlinks from a 6U CubeSat in low-Earth orbit (LEO) and has delivered up to 4.8 terabytes (TB) error-free in a 5-minute pass. In total, 65 passes have been performed since launch in May 2022, with 22 of those passes conducted in April-May 2023. The TBIRD space and ground terminals leverage commercial fiber-coupled coherent transceivers along with a custom Automatic Repeat reQuest (ARQ) protocol to ensure error-free communication through the atmospheric fading channel. This paper presents data throughput results from the on-orbit passes and an analysis of the ARQ system operation that shows that near-optimal performance was achieved. Results from Doppler compensation experiments that increased the data volume per pass are also presented.**

I. INTRODUCTION

NASA's Terabyte Infrared Delivery (TBIRD) program has developed a LEO direct-to-Earth architecture for delivering enormous data volumes using high-rate optical communication downlinks with small size, weight, and power terminals [1], [2]. Even though LEO-to-ground passes are less than 10 minutes long, bursting at 200-Gbps for just a few minutes results in multiple terabytes transferred from space to ground. Small terminals with such capability are enabled by utilizing compact, low-power 100-Gbps coherent transceivers from the terrestrial fiber telecommunications industry [3], [4]. Another key element of the architecture is a terabyte-class buffer capable of sensor data ingestion at a moderate rate and high-speed readout during an optical downlink.

To demonstrate this architecture, the TBIRD flight mission was developed, with space and ground elements shown in Figure 1 [5]. The 3U payload, built by MIT Lincoln Laboratory, is hosted by the Pathfinder Technology Demonstrator 3 (PTD-3) 6U CubeSat supplied by Terran Orbital [6]–[8]. The payload uses two dual-polarization QPSK transceivers operating on different wavelength channels to downlink in 100-Gbps mode (one transceiver) or 200-Gbps mode (two transceivers). When operating in 200-Gbps mode, the power draw is 100 W. The payload relies on the spacecraft to body-point and provides feedback at 10 Hz for the bus to track.

The ground station is NASA JPL's Optical Communications Telescope Laboratory (OCTL), which has a 1-meter diameter telescope with adaptive optics to couple the received signal into single-mode fiber [9].

Terrestrial fiber transceivers are designed to operate over static fiber channels and are not natively equipped to handle data outages resulting from atmospheric fading. A common technique for atmospheric mitigation in free-space laser communication systems is to interleave forward error correction (FEC) codewords to achieve temporal diversity, but this was not possible in the TBIRD architecture because the soft-decision FEC is implemented internal to the black-box commercial transceivers. Instead, TBIRD uses a custom Automatic Repeat reQuest (ARQ) protocol that is implemented in an FPGA external to the transceivers [10]. The protocol uses a return channel (uplink) to request retransmission of unreceived data and thereby ensure error-free data delivery. The TBIRD uplink is a 2-kbps optical ground-to-space link that supports the ARQ protocol and also serves as a tracking beacon for the closed-loop body pointing of the satellite [11].

One of the main objectives of the TBIRD mission was to demonstrate an efficient ARQ system that can be used with commercial transceivers to communicate error-free through space-to-ground atmospheric channels. Terrestrial coherent transceivers are also not necessarily designed to accommodate the large clock and optical carrier frequency offset that occurs due to Doppler shift in a LEO-to-ground link. Another objective of the TBIRD mission was to assess the capability of the commercial transceivers to tolerate and compensate for Doppler in this environment.

On May 25th, 2022, the PTD-3 spacecraft was deployed to a 530-km sun-synchronous orbit (which as of this writing

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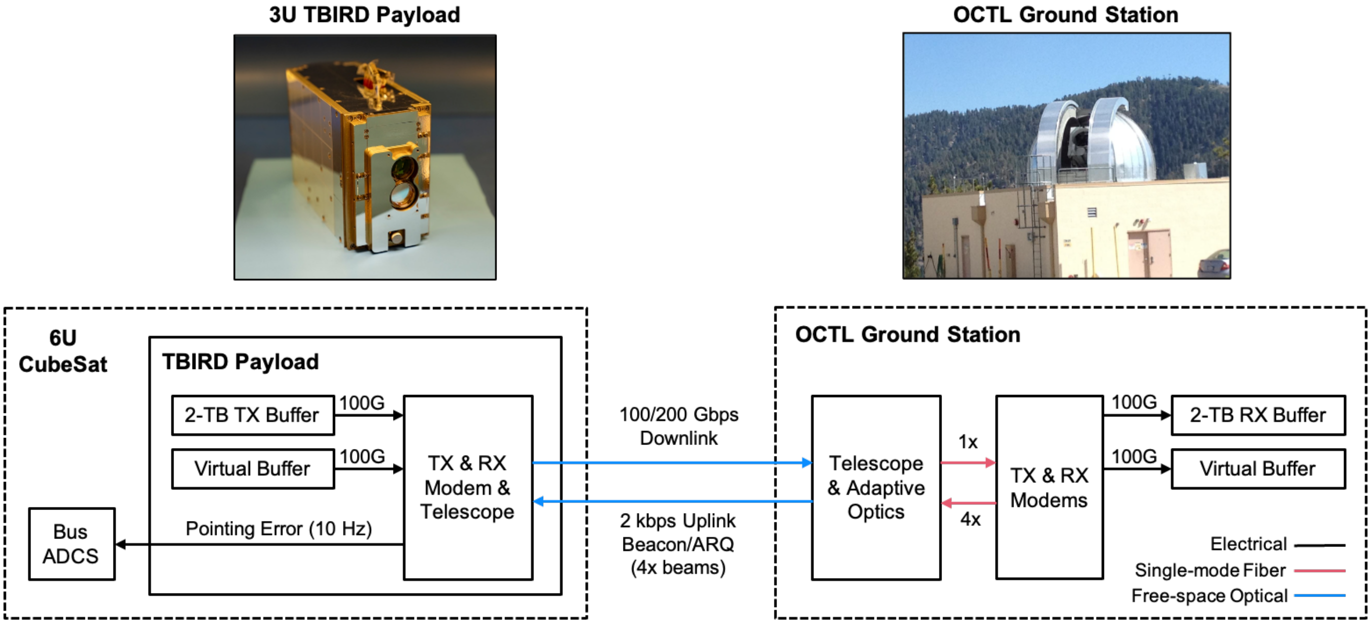

Fig. 1: The TBIRD mission architecture enables buffer-to-buffer transfer from LEO-to-ground over a 100 or 200 Gbps downlink. A low-rate optical uplink supports an automatic repeat request (ARQ) protocol to ensure error-free data delivery and also serves as a beacon for spatial tracking to provide pointing feedback to the spacecraft bus.

has now naturally decayed to around $450\,\mathrm{km}$). In the first year of its mission, TBIRD successfully demonstrated novel capabilities in nanosatellite body pointing (less than $10\,\mu\mathrm{rad}$ RMS pointing error) and 200-Gbps data delivery (up to $4.8\,\mathrm{TB}$ error-free in a single pass). To our knowledge, TBIRD has demonstrated the fastest downlink ever achieved from space.

This work presents on-orbit performance results for the TBIRD communication and ARQ system, with a focus on the more recent second mission “campaign” during April–May 2023. In Section III, the corpus of mission telemetry is used to assess various performance aspects of the ARQ system, in particular showing that the system was highly efficient (85-95%). Section IV details measurements of Doppler tolerance for the on-orbit system and how Doppler was compensated during passes, leading to increased data volume.

Previous publications detail many aspects not covered here, such as lasercom pass operations flow, pointing acquisition and tracking results, link budgets and models, and link performance during the first campaign (June–November 2022) [12]–[14].

II. Mission Campaigns

Shortly after launch, lasercom downlinks began in June 2022 and continued until November 2022, concluding the nominal 6-month mission (Campaign 1). During the subsequent intermission period, payload health checks were performed weekly but the ground station was not utilized for the TBIRD mission. Link operations resumed at OCTL for a 2-month campaign in April–May 2023 (Campaign 2). There were notable improvements in Campaign 2 compared to Campaign 1, primarily as result of better fiber coupling performance at the ground station.

Campaign 1 (June – November 2022)

In Campaign 1, 43 lasercom passes were executed, with link operations running smoothly within the first few passes. Due to the sun-synchronous nature of the orbit, passes occurred at either 2PM (daytime) or 2AM (nighttime) local ground station time.

Throughout both campaigns, the spacecraft pointing was very consistent and the irradiance at the ground station was in agreement with link budget models for the duration of the pass [13]. This can be seen in the “power-before-fiber” red curve in Figure 2. The power before fiber is the free-space power just before coupling to single mode fiber, which was estimated by applying a calibration to wavefront sensor (WFS) telemetry.

The primary limitation on system throughput during Campaign 1 was the fiber coupling performance of the ground station (see Figure 2, power-in-fiber). Passes in June 2022 downlinked over $0.5\,\mathrm{TB}$ error-free, but fast, deep power fluctuations – beyond what would be expected due to atmospheric turbulence – prevented sustained high throughput during passes. For reference, the transceiver FEC threshold is around $-41\,\mathrm{dBm}$ in 100-Gbps mode. One issue was that the WFS saturated near the peak of the passes, resulting in very poor coupling at high elevation angles. Toward the end of Campaign 1, the WFS integration time was reduced from $20\,\mu\mathrm{s}$ to $10\,\mu\mathrm{s}$ which led to significant improvement at high elevation angles (above $60°$).

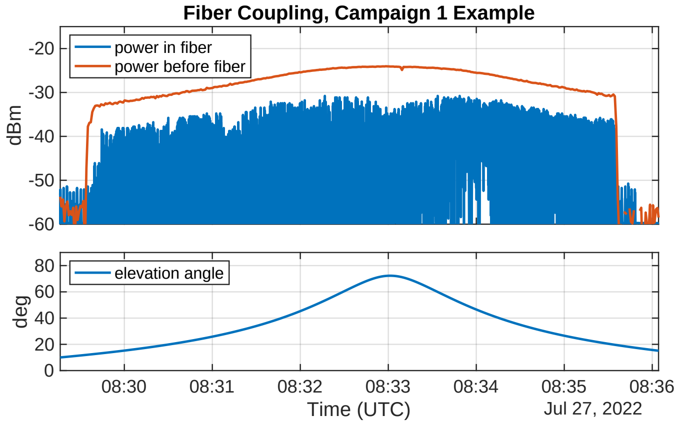

Fig. 2: Example of typical power in fiber during Campaign 1. Nighttime pass with measured r_0 of 6–11 cm (referenced to 500 nm at zenith).

Campaign 2 (April – May 2023)

Campaign 2 consisted of 22 passes, coincidentally 11 daytime and 11 nighttime. This was a compressed timeline relative to Campaign 1 and ideal link conditions (e.g. nighttime, clear skies) were much less common.

However, for much of Campaign 2, the fiber coupling performance was markedly better across all elevation angles. Periods of deep signal extinction were still present, but for a much smaller proportion of the pass than generally seen during Campaign 1. Figure 3 shows an example from May 11, 2023, a daytime pass. Ground instruments measured an atmospheric coherence length r_0 of 2–4 cm on this pass that was significantly worse than the r_0 of 6–11 cm of the nighttime pass in Figure 2, but the fiber coupling was actually significantly better at both low and high elevation angles. This improvement can be seen in terms of the depth of the fluctuations and the decreased gap between power-before-fiber and power-in-fiber.

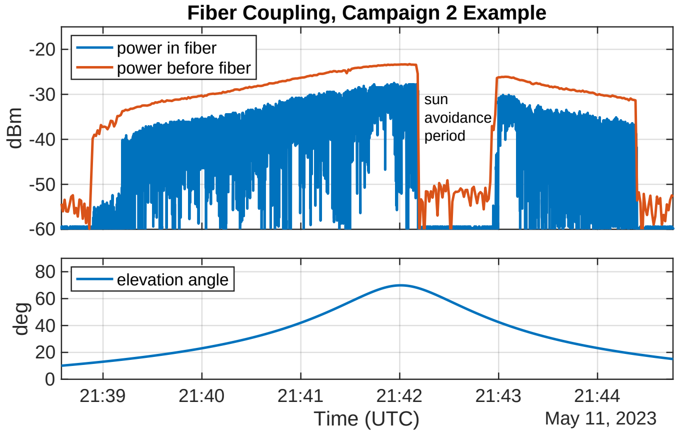

Fig. 3: Example of the improved power in fiber during Campaign 2. Daytime pass with measured r_0 of 2–4 cm (referenced to 500 nm at zenith). In this particular pass, the ground telescope was offset for a conservative period to avoid a close sun angle.

Figure 4 shows the cumulative data transfer achieved over the 22 passes. Over 33 TB were downlinked error-free, yielding an average of 1.5 TB per pass over the campaign. The highest data volume delivered in a single pass was 4.8 TB over the course of about 5 minutes (1 TB per minute). Notably, the objective of each pass was not necessarily to maximize data volume; for example, there were several passes during which the spacecraft was executing a controlled wide-pointing scan to measure downlink beam characteristics. Furthermore, several passes were partially or very cloudy.

Improved power-in-fiber was the primary reason for the significant increase in data volumes achieved in Spring 2023. Another contributor is that many more passes in Campaign 2 were operated in 200-Gbps mode, whereas Campaign 1 passes were almost exclusively in 100-Gbps mode. The 200-Gbps mode closed at higher elevation angles and thus for less time than the 100-Gbps mode, but generally netted higher data volume.

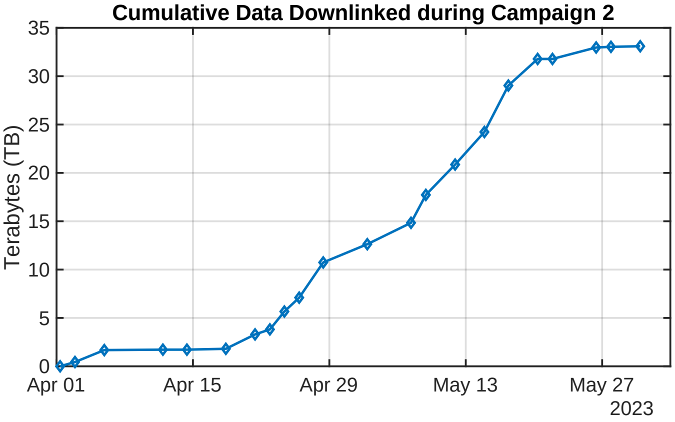

Fig. 4: Cumulative data volume downlinked error-free over 22 passes during Campaign 2. Average data volume per pass exceeded 1.5 TB, despite occasional cloudy passes and numerous experiments that were not targeted at maximizing data volume.

III. ARQ PERFORMANCE RESULTS

In both campaigns, the TBIRD ARQ system operated successfully and enabled the reliable, error-free transfer of terabytes of data from the space buffer to the ground buffer. In 200-Gbps mode, the space buffer was augmented with a “virtual buffer” of pseudo-data because the SSD buffer was limited to 100-Gbps readout. However, extensive system telemetry recorded during passes was used to assess the ARQ performance in the absence of byte-by-byte buffer comparisons.

In LEO-to-ground links, fading due to atmospheric turbulence can have a coherence time as low as ~ 1 ms. The TBIRD ARQ system was therefore designed to achieve high throughput efficiency in the presence of millisecond-class fluctuations in received power. The implementation is a custom selective-repeat protocol that multiplexes stop-and-wait ARQ subsystems to form a set of virtual channels with no idle transmission time (Figure 5). A single ARQ frame spans both wavelength channels and is composed of thousands of microsecond duration Ethernet frames. If any of these Ethernet frames are dropped, the entire ARQ frame is dropped and a retransmission is requested.

The uplink repeatedly sends positive acknowledgements of ARQ frames that are successfully received at the ground terminal. An ARQ message consists of one bit per virtual channel; there are 1752 virtual channels so that the each message fills most of the payload of a single Reed-Solomon (223,255) uplink codeword. A cyclic redundancy check (CRC) appended to each ARQ message allows the uplink receiver at the space terminal to detect whether the message is valid or not. When a valid uplink message is received, the space terminal updates the status of all the virtual channels. New ARQ frames are transmitted for channels that acknowledged reception, while all other channels require retransmission of their ARQ frames.

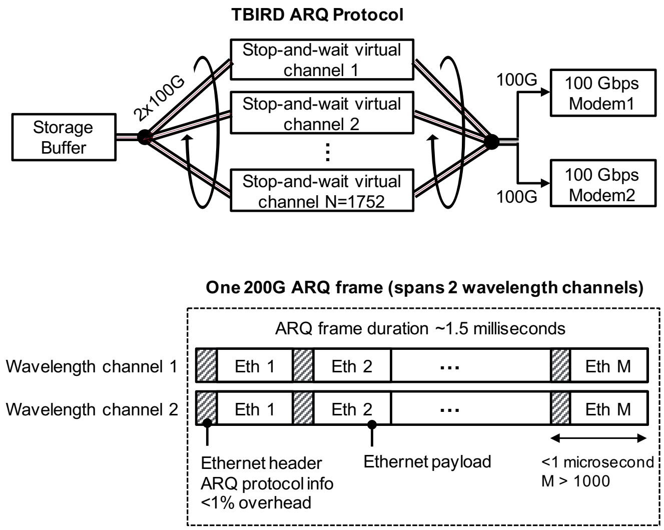

Fig. 5: (top) The TBIRD ARQ protocol cycles through virtual stop-and-wait channels with no idle transmission time. (bottom) A TBIRD ARQ frame is $\sim$1.5 ms long and comprises 1000s of Ethernet frames. The entire ARQ frame is dropped if one or more of its Ethernet frames are not received.

ARQ System Efficiency

The ARQ-protected throughput is the error-free data rate of the downlink, which is less than the transceiver rate of 100 or 200 Gbps when power fluctuations at the ground receiver cause ARQ frames to be dropped. Only unique ARQ frames are counted towards the throughput; if, for some reason, a particular ARQ frame is received multiple times, only the first time counts.

The "Ethernet data rate" of the system is defined as the total number of bits per second of Ethernet payload data successfully received at the ground terminal, regardless of whether those payloads have already been received. In 200-Gbps mode, the Ethernet data rate is the sum of the individual Ethernet data rates of the two 100-Gbps receivers.

The Ethernet data rate is always greater than or equal to the ARQ throughput. One can use the Shannon capacity of erasure channels to show that the Ethernet data rate is an appropriate benchmark for evaluating the efficacy of the ARQ system [10], [11]. An optimal ARQ system for the TBIRD mission would yield ARQ throughput equal to the Ethernet data rate.

Figure 6 shows the ARQ throughput and the Ethernet data rate for TBIRD pass on May 17, 2023. At elevation angles above $\sim$30°, the throughput is 150–200 Gbps. At lower elevation angles, the data rate is still significant, but many more retransmissions are needed due to increased fading-induced outages. Nonetheless, at both high and low elevation angles, the ARQ throughput is always close to the Ethernet data rate, which indicates that the ARQ system is efficient across a wide range of link conditions.

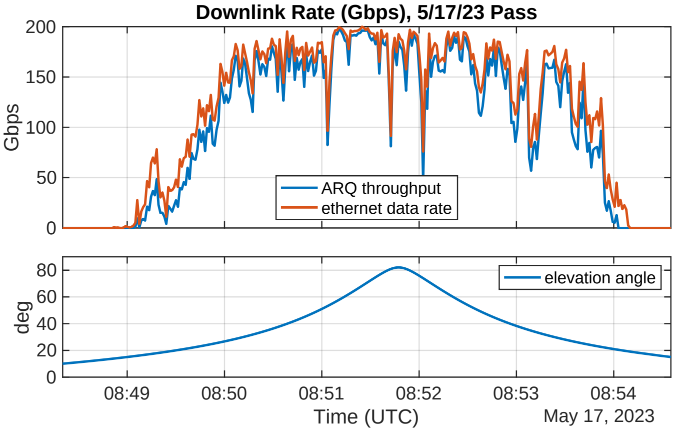

Fig. 6: ARQ-protected throughput and Ethernet data rate during the 5/17/23 pass. The similarity in the two rates indicates an efficient ARQ system.

For LEO-to-ground passes, a natural way to measure the efficiency of the ARQ system is to compare the total ARQ-protected data volume to the Ethernet data volume:

$$\text{ARQ efficiency} = \frac{\text{ARQ-protected data volume}}{\text{Ethernet data volume}} \tag{1}$$

For the 5/17/23 pass, the ARQ data volume was 4.8 TB and the Ethernet data volume was 5.4 TB, which was an ARQ efficiency of 90%.

Figure 7 summarizes the ARQ efficiency of all the passes during Campaign 2 that delivered more than 1 TB, plotted against the Ethernet data volume of the pass. In general, the ARQ system was highly efficient (85-95%). One obvious trend is that higher data volumes had higher ARQ efficiency. This is likely because lower data volumes were the result of more extreme power fluctuations, and excessive power fluctuations could cause an ARQ frame to drop even though most of its Ethernet frames are received. Another observation is that the 100-Gbps mode passes had the highest efficiency (95%). The lower efficiency for 200-Gbps mode may have been caused by slightly unequal power received on the two wavelength channels. An ARQ frame spans both channels and the entire frame would be dropped if just one Ethernet frame on one of the channels were dropped. Steps were taken to balance the channels prior to Campaign 2, but there was likely some residual imbalance.

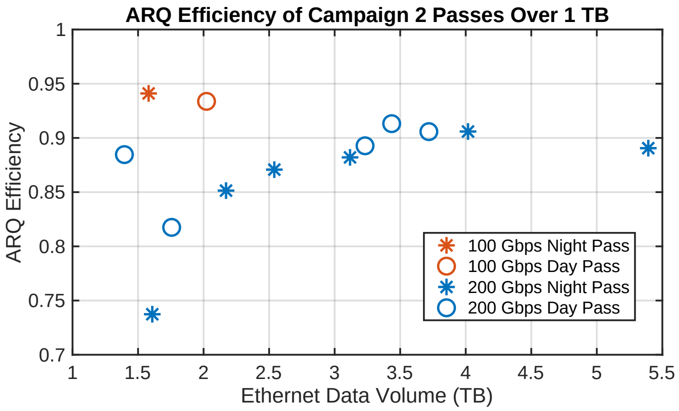

Fig. 7: ARQ efficiency, defined in (1), for all Campaign 2 passes whose data volumes exceeded 1 TB. The passes in 100-Gbps mode achieved the highest efficiency.

Other feasible factors of inefficiency are listed in Table I, along with their particular impact on the TBIRD mission. Most of these factors were negligible or non-existent by design in the TBIRD ARQ system. Any future lasercom system that includes an ARQ technique should consider these factors in evaluating different possible approaches.

TABLE I: List of feasible ARQ inefficiencies and their impact on the TBIRD ARQ performance.

Inefficiency factor	**Impact on TBIRD**
ARQ framing overhead	Negligible ($< 1\%$)
Retransmitting before full round trip time elapses	Non-existent by design
Idle transmission while waiting for acknowledgements	Non-existent by design
Dropped ARQ messages on uplink	Negligible
Excessively fast fluctuations in power-in-fiber	Moderate
(200G Mode) RX power imbalance in wavelength channels	Low

ARQ Quality of Service

At any point during the pass, some amount of data has been transferred error-free, but it is not all contiguous because some ARQ frames may still need to be retransmitted. Eventually those gaps would be filled in if the system operated for long enough, but a LEO-to-ground pass is short event, only a few minutes long. So, at the end of the pass, there are inevitably some data gaps that would need to wait until the next pass to be filled in.

From a quality of service perspective it is desirable that the contiguous portion transferred is as large as possible. This is analogous to transferring a large file with zero errors during the pass and being able to release the file from the space buffer at the end of the pass so that a new sensor data file can be written in its place.

If the earliest gap occurs at byte M+1, then the first contiguous M bytes were transferred successfully. If N is the total number of bytes transferred error-free, then a relevant quality of service metric is the ratio M/N. The ARQ system telemetry recorded at the TBIRD ground terminal made it possible to calculate this quality of service metric in post-processing, even though the downlinked data was not actually written to the SSD buffer in many of the passes.

Figure 8 shows the ARQ quality of service during the 5/17/23 pass. The fact that the contiguous portion (red) is close to the total error-free transfer (blue) indicates that the ARQ system was timely in filling in the data gaps as the pass progressed. At the end of the pass, the total error-free data volume was $4.8\,\mathrm{TB}$, while the contiguous portion of the transferred buffer was $4.5\,\mathrm{TB}$, so the quality of service metric was 94%. Other passes achieved similar quality of service.

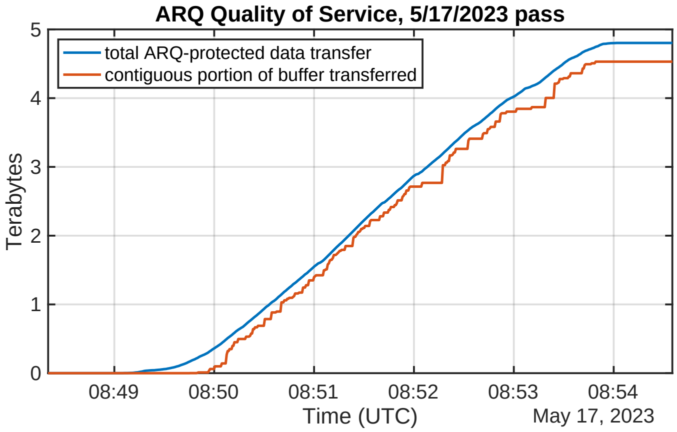

Fig. 8: ARQ quality of service assessment for the 5/17/23 pass.

ARQ Summary

The TBIRD ARQ system was highly efficient and achieved excellent quality of service, as presented in the previous sections. These are two critical performance metrics for a buffer-and-burst system such as TBIRD that envisions sensor data being accumulated on a large buffer and then downlinked during a short contact to a delay-tolerant user. Other systems may want to operate in more of a real-time manner and prioritize minimizing latency and/or buffer size. In that case, the relevant metrics would likely be different.

IV. DOPPLER TOLERANCE AND COMPENSATION

One objective of the TBIRD mission was to assess the capability of the commercial transceivers to tolerate and compensate for Doppler in this environment. Due to the black-box nature of the transceivers, it was not feasible to carry out a lab-level test that fully emulated the effects of Doppler. One particular obstacle was not being able to externally adjust the oscillator for the symbol clock.

Nevertheless, the advertised clock and carrier tolerances indicated that the performance would be acceptable for the elevation angles of interest during a LEO-to-ground link. The TBIRD system was intended to operate at higher elevation angles, which have lower Doppler shifts.

During passes with good power-in-fiber performance at the ground station, the TBIRD downlink was able to close at lower elevation angles, pushing into the regime where Doppler-related thresholds became apparent and clearly were restricting the potential data volume of passes. This was most evident during Campaign 2 when the ground terminal fiber coupling improved. For example, Figure 9 shows that the measured throughput (blue curve) dropped to zero abruptly during the descent of the pass. There are a number of reasons that could cause a downlink to drop out, but in this case the system continued to receive sufficient power in fiber that should have been enough to achieve non-zero throughput (see model, red curve). The lower plot in Figure 9 shows the Doppler shift (in parts per million) during this particular pass, which had a peak elevation angle of 60°. A pass with a higher peak elevation angle would have a different Doppler profile with larger shifts across all elevation angles. In this pass, the threshold during the descent was approximately $-16\,\mathrm{ppm}$.

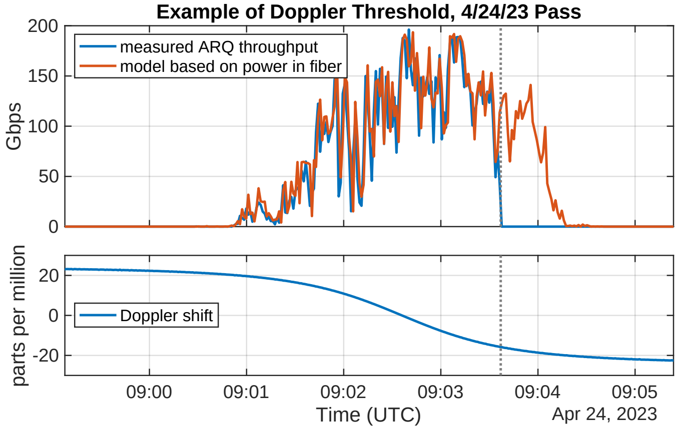

Fig. 9: Measured throughput compared to a model informed by power-in-fiber in the 4/24/23 pass. The comparison indicates that the Doppler shift exceeded the tolerance of the system. In later passes, Doppler compensation was used to avoid this limitation and increase the data volume.

The Doppler tolerance of the two downlink channels was estimated from aggregated telemetry of passes in Campaigns 1 and 2 (Figure 10). For each pass, the timestamp of the first and last received Ethernet frame during the pass was obtained; pairs of (Doppler shift, link range) that occurred at those timestamps are the basis for the scatterplot. The fact that the Doppler shift is roughly constant regardless of link range shows that the reason for the downlink halting was due to Doppler and not due to loss of signal power. The window is seen to be roughly $-17\,\mathrm{ppm}$ to $21\,\mathrm{ppm}$.

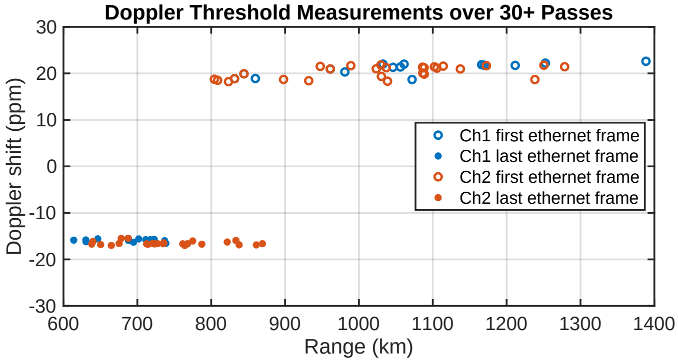

Fig. 10: Aggregated telemetry taken over more than 30 passes was used to measure the Doppler tolerance window of the TBIRD system when Doppler compensation was not employed. For both channels, the window was approximately $-17\,\mathrm{ppm}$ to $21\,\mathrm{ppm}$.

Doppler Compensation

Starting in the middle of Campaign 2, experiments were performed to compensate for Doppler during a pass and thereby increase the data volume. This was done by tuning the optical local oscillator (LO) of the ground terminal transceivers. Prior to the pass, the LO was shifted by about $+1.5\,\mathrm{GHz}$ from nominal, corresponding to $\sim 8\,\mathrm{ppm}$ at the $1.5\,\mu\mathrm{m}$ wavelength. At the peak of the pass, the LO was shifted in the opposite (negative) direction by about $-3\,\mathrm{GHz}$. These offsets effectively shifted the Doppler tolerance window to accommodate Doppler down to very low elevation angles where the signal power was not sufficient close the link.

As one example of the data volume increase achieved in the TBIRD mission due to Doppler compensation, consider the 5/17/23 pass whose throughput is shown in Figure 6. In this pass, Doppler was fully compensated and the data volume was $4.8\,\mathrm{TB}$. However, if compensation had not been applied, i.e. if the Doppler tolerance window of $-17\,\mathrm{ppm}$ to $21\,\mathrm{ppm}$ had not been adjusted at all, then the data volume would have been approximately $3.3\,\mathrm{TB}$, a reduction of 30%. The data volume difference was more pronounced in this pass compared to other passes because the peak elevation angle was very high (82°), but the effect of compensation was generally significant in passes that implemented it.

V. SUMMARY

Since launch in May 2022, the TBIRD mission has demonstrated 100-Gbps and 200-Gbps downlink rates from a nanosatellite in LEO to the OCTL ground station. The Spring 2023 campaign consisted of 22 passes executed over 2 months, with an average data volume of $1.5\,\mathrm{TB}$ per pass and a maximum of $4.8\,\mathrm{TB}$ downlinked in a single pass. The TBIRD mission has demonstrated that commercial coherent transceivers can be leveraged to achieve reliable, high-volume communication from space to ground. Throughout the mission, the ARQ system has enabled error-free data transfer in the presence of atmospheric fading and has been highly efficient (85-95%). Doppler compensation via transceiver LO tuning during a pass increased data volume.

VI. ACKNOWLEDGEMENTS

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